Outer Atmospheres of Cool Stars Observed with IUE

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I. INTRODUCTION

The outer atmosphere of the Sun is a plasma where complex magnetic fields play a prevailing role. The magnetic fields not only govern the morphology but also influence the energy balance throughout the outer atmosphere. The magnetic field varies, in strength and structure, over a wide range of temporal and spatial scales. These variations in the magnetic field of the solar atmosphere produce the myriad of time-variable phenomena labeled "solar activity." The importance of magnetic fields in solar activity is underscored by the wide variety of phenomena controlled by the interplay of magnetic fields, from ephemeral solar flares to the long-term sunspot cycle.

The chromosphere, transition region, corona and solar wind comprise the outer solar atmosphere. The temperature in these outer layers can be vastly hotter than that of the solar photosphere. The elevated temperatures are powered by heating mechanisms that dominate the radiative losses and other cooling mechanisms in these layers (cf. Stein and Leibacher 1974; Linsky 1980; Baliunas 1983). In the quiet Sun, for example, the gradual rise in temperatue through the chromosphere ($5000 \lesssim T \lesssim 20{,}000$K) is partially caused by the damping of short-period acoustic waves generated by the subsurface convective layer (cf. Ulmschneider 1981; Ulmschneider and Stein 1982). The sharp increase in temperature through the transition zone ($20{,}000\text{K} \lesssim T \lesssim 10^6$K) is fueled by the loss of efficient radiators present in the lower chromosphere (for example, H I Ly α, Ca II H and K and Mg II h and k emissions) and by conductive heating downward from the corona. The temperature of the corona ($T \sim 1\text{-}2 \times 10^6$K) is likely maintained by the deposition energy by magnetic mechanisms offset by partial cooling provided by the solar wind and by radiative cooling in the X-ray and extreme ultraviolet spectrum. Such a simplified picture neglects the imperspicuous impact of, for example, magnetic processes which may also be a source of non-radiative heating in the outer solar atmosphere (cf. Stein and Leibacher 1974; Ulmschneider and Stein 1982).

Studies of the outer atmosphere of the Sun and its magnetic fields benefited greatly from ultraviolet and X-ray measurements over the past two decades. The visible face of the solar photosphere and glimpses of the chromospheres available from the ground were augmented by high-spectrum and spatial-resolution observations of the chromosphere, transition region and corona and solar wind available from space-based missions such as Skylab/Apollo Telescope Mount. Theoretical modeling has made great strides in our understanding of the energy balance through the outer solar atmosphere and the mechanisms

powering solar magnetic phenomena.

Fundamental studies of stellar chromospheres of cool stars were accomplished about three decades ago from ground-based observations, primarily of the Ca II H and K emission cores. Stellar activity in the guise of the Ca II H and K cores was noted to be ubiquitous among stars later than about spectral type mid-F. It is reasonable to assume that the impact of magnetic fields on the Sun is similar to that inferred from Ca II emission on other stars. It is also tempting to assume that the mechanisms powering the entire solar atmosphere, not only the chromosphere, are valid for other stellar atmospheres as well. Under the tutelage of solar activity, studies of stellar activity in cool stars burgeoned with the opening of X-ray and ultraviolet windows. The experiments on satellites, for example, SAS-3 and *Copernicus*, along with rocket-borne experiments of the early 1970's, indicated the direction along the road paved by recent satellites such as HEAO-1, HEAO-2 and *IUE*. The *IUE* satellite has opened a window into the ultraviolet spectrum in a variety of cool stars, many of which resemble the solar ultraviolet spectrum, and many of which do not. *IUE* is providing guidelines for theoretical work on atmospheric heating mechanisms which is driven by logical positivism.

In a way similar to the studies of stellar chromospheric Ca II H and K of 30 years ago we seek answers to questions such as: Are the mechanisms exciting the outer solar atmosphere present on other stars? What influences and controls these processes, and in particular, what is the role of the magnetic fields? Ultraviolet observations of cool stars in conjunction with coronal X-ray or ground-based chromospheric measurements, or both, have served both to refine and to define our understanding of stellar activity.

The sensitivity of *IUE* down to a reasonable limiting magnitude put many different stars' ultraviolet spectra at our fingertips. Understanding of stellar activity throughout stellar atmospheres has progressed because we can observe in the ultraviolet particular stars in great detail and many stars in snapshot surveys.

II. RESULTS OF ULTRAVIOLET SURVEYS

The advent of *IUE* provided ultraviolet spectra of stellar chromospheres, transition regions, and winds indicated by features accessible to the range 5×10^3 - 2×10^5K. Figure 1 (upper panel) shows the low-dispersion, short-wavelength spectrum of a dwarf star, ξ Boo A (G8V), with relatively strong chromospheric emission compared to the quiet Sun. The canonical "solar-like transition-region features" such as Si IV (λ1400), C IV (λ1550) and N V (λ1240) indicate the presence of plasmas of temperatures up to $T \sim 2 \times 10^5$K, the temperature of formation of N V, in the dwarf ξ Boo A. There is bright Mg II h and k (λ2800) chromospheric emission in this active star as well. On the other hand, the cool giant β And (MO III), while lacking in observable amounts of high-temperature transition-region material typified by C IV and N V, does show chromospheric emission formed at temperatures less than 20,000K (lower panel, Figure 1). In addition to these two broad categories of short-wavelength *IUE* spectra, namely, the "solar-like" and "non-solar-like" transition-region spectra,

there is a third. The supergiant α Aqr (G2Ib) (middle panel, Fig. 1) possesses not only a "solar-like" transition region with N V, C IV and Si IV, but also evidence of a strong wind in the form of Mg II circumstellar absorption blue-shifted by about -70 km s^{-1}. The supergiant α Aqr is one of the "hybrid" stars. Winds and mass loss will be discussed further below, following an investigation of the parameters governing ultraviolet emission in dwarf stars.

A. Chromospheric Emission in Main-Sequence Stars

Along the lower main sequence, the chromospheric emission strength denoted by Ca II H and K emission is correlated with relative youth and rapid rotation in single stars. It should be noted parenthetically that rapid rotation can be the result of youth or duplicity, a condition inducing rapid rotation by tidal forces in close binary systems. The conclusion that chromospheric emission decays with time for single, main-sequence stars resulted from studies of stars whose ages could be determined, either by membership in galactic clusters or by models of lithium depletion in field stars (Wilson 1963; Skumanich 1972; Duncan 1981). Further, for dwarf stars of a given mass, Ca II chromospheric emission was linearly correlated with rotational velocities (Kraft 1967; Skumanich 1972; Soderblom 1982). The dependence of emission upon rotation and the decay of emission with time led to the conclusion that rotation and emission decreased approximately with a square-root dependence on stellar main-sequence age (Skumanich 1972). Qualitatively, the action of a magnetic dynamo links the stellar magnetic fields and rotation with chromospheric, and presumably coronal emission (cf. Skumanich and Eddy 1981).

With *IUE* the chromospheric indicator provided by the flux in the Mg II h and k emissions can be investigated among main-sequence stars. Two parallel studies of the dependence of Ca II H and K (Noyes *et al.* 1984) and Mg II h and k (Hartmann *et al.* 1984*a*) show the same phenomena controlling both chromospheric indicators. In Figure 2, the total stellar surface flux in Mg II (h + k), normalized by the stellar bolometric luminosity, is plotted as a function of the quantity (τ/P) in main sequence stars. The quantity P is the measured rotation period (Vaughan *et al.* 1981, Baliunas *et al.* 1983*a*), and τ is a function of (B-V) color, or equivalently, the lower main-sequence mass, only. Noyes *et al.* (1984) suggested that τ could represent the convective turnover time for stellar interior models where the mixing-length parameter α = 2 pressure scale heights. The solid line is the vertically-scaled relation for the (Ca II, τ/P) fifth derived by Noyes *et al.* 1984).

As expected, Mg II, as well as Ca II, is not only dependent upon rotation, but also on color, or main-sequence mass. The small scatter for both Mg II and Ca II reveals that both rotation and main-sequence mass, or by inference, convective zone properties, dictate the level of chromospheric emission in dwarf stars. The ratio of the convective turnover time to the rotation period is the inverse of the Rossby number, a parameter fundamental in stellar dynamo theory (cf. Parker 1979). This important result indicates that there is a single determinant of chromospheric activity in lower main-sequence stars that is characterized by the Rossby number and therefore closely linked to dynamo theory.

B. Transition-Region Emission in Main-Sequence Stars

Among the dwarf stars, rapid rotation produces enhanced fluxes in, for example C IV (Hartmann *et al.* 1979; Schrijver *et al.* 1984), the expected result because the transition-region emission is well-correlated with chromospheric fluxes (Hartmann *et al.* 1979; Dupree *et al.* 1979; Ayres *et al.* 1981; Hartmann *et al.* 1982*a*). As a function of age, the cool dwarf stars, from T Tauri stars to the Sun, show a pronounced decay of flux with time (Boesgaard and Simon 1982; Walter *et al.* 1984). The fluxes of the high-temperature species, such as He II, C II, C IV, N V and Si IV, are approximately inversely proportional to age, unlike the chromospheric emissions that show a dependence of fluxes proportional to the inverse square root of time. The different behavior of the chromospheric and transition region fluxes as a function of activity level can be stated alternatively. Figure 3 shows the surface fluxes, relative to those of the quiet Sun, for a variety of stars. The quiet dwarf δ Pavonis has a relative paucity of the transition-region material, while active dwarf stars, whose surface fluxes can be factors of 10-100 above that of the quiet Sun, display an increasing enhancement of high-temperature gas as flux levels increase (Hartmann *et al.* 1979; Ayres *et al.* 1981; Hartmann *et al.* 1982*a*). With greater activity, the emission increases faster in the transition region than it does in the chromosphere.

This behavior was noted for the active portions of the Sun relative to the quiet (Dupree *et al.* 1973) and other active-chromosphere stars observed with *IUE* whose surface fluxes and transition-region pressures are similar to those in the active Sun (Dupree *et al.* 1979; Baliunas *et al.* 1979; Ayres *et al.* 1981; Hartmann *et al.* 1982*a*). Undoubtedly the increased role of conduction in dominating the radiative losses in these higher-pressure transition regions of the active stars causes the relative enhancement of the fluxes of the high-temperature ions, as inferred from the quiet and active Sun (Dupree *et al.* 1973; Baliunas and Dupree 1982).

In dwarf stars, a comparison of the total radiative losses in the chromosphere, transition region and corona suggests that for quiet-chromosphere stars, the chromospheric losses dominate. With increasing activity, the losses throughout the atmosphere increase in a comparable fashion. Hence, the enhancements become largest in the transition region and corona as activity levels progressively increase among stars (Hartmann *et al.* 1982*a*; Hartmann 1983; Hammer *et al.* 1982).

The relative emission measures for the transition region and X-ray measurements agree reasonably well with simple, static "loop" models such as those of Rosner *et al.* (1978; cf. Hartmann *et al.* 1982*a*). Because these loop models explain a range of chromospehric activity in dwarf stars, energy budgeting processes found on the Sun must also behave similarly in other stars.

C. Chromospheric and Coronal Emission in Giant Stars

A survey of F5 III-KO III stars with *IUE* (Simon 1984) reveals that the C IV flux, as a fraction of bolometric luminosity, increases from F5 III to a

maximum at GO III, then sharply declines to limits of detectability at type KO III. The stars earlier than about G2 III are first crossing stars, that is, they are in a state subsequent to departure from the main sequence but prior to ascension to the red-giant branch where helium ignites in the core. The relative increase in C IV fractional emission between F5 III and GO III might be attributed to the development of convective zones that power the chromospheric emission in these stars. In addition, Simon (1984) finds a good correlation between fractional C IV flux and projected rotational velocity. Thus, for giant stars initially exiting from the main sequence, the chromospheric and coronal emission is controlled by the same factors as in main-sequence stars: rotation and depth of the convective zone.

Beyond the spectrum type of late G-giants, however, the sample of giants becomes mixed with second crossing, or post helium flash, stars and the picture of chromospheric and coronal emission becomes murky. One puzzle, however, is apparent among these evolved cool stars. In the Hyades, there are four KO III cluster stars that are presumably homogeneous and coeval. The range in C IV emission is at least a factor of six (see Figure 4) and no obvious macroscopic parameter, such as age or rotation can reasonably account for the discrepancy (Baliunas *et al.* 1983*b*; Böhm-Vitense 1984). Two proposals have been forwarded to account for the range in ultraviolet emission in these stars. For example, the Hyades giants do differ slightly in photospheric effective temperature (but only by as much as about 200K) and a steep dependence of chromospheric heating may exist to produce the wide range of C IV emission (Böhm-Vitense 1984). Alternatively, the giants may have been sampled at random phases of long-term activity cycles analogous to those common in main-sequence stars (Baliunas *et al.* 1983*b*). In either case, the disparity in emission levels in stars thought to be so similar in macroscopic characteristics indicates that a hidden parameter controlling the emission in evolved stars remains to be discovered.

D. Winds and Mass Loss in Evolved Stars

For evolved stars, chromospheric emission is also present, and in addition the extended atmospheres of these stars are cool and can possess strong winds and circumstellar shells. Compared to solar wind, with a temperature of $T \sim 10^6$K, and a mass loss rate, $\dot{m} \sim 10^{-14}$ $M_\odot$ yr^{-1}, the winds in giants and supergiants reach temperatures of only $T \sim 10^4$K with large mass loss rates, $\dot{m} \sim 10^{-6}$ $M_\odot$ yr^{-1} (Linsky and Haisch 1979; Hartmann *et al.* 1982*a*).

These extremes in the winds of cool stars are readily observable in the ultraviolet with *IUE*. On the one hand, the "solar-type" outer atmosphere, showing as it does a temperature rise of over two orders of magnitude from the chromosphere to the wind produces signatures of plasmas accessible from *IUE* from T ~ 5000 to 200,000K. On the other hand, a cool giant star(for example, β And, Fig. 1) lacks observable amounts of these ions and this lack would suggest little gas, if any, exists at temperatures of $T \sim 10^5$K. Spectrum features seen in the ultraviolet in β And are formed at temperatures cooler than about 20,000K. While β And does possess a chromosphere, it does *not* maintain a "solar-like" transition region. The hot transition zones avoid stars in the upper

right of the H-R diagram.

This dichotomy between "solar-like" and "nonsolar-like" outer atmospheres (Linsky and Haisch 1979) is also manifest in the chromospheric Mg II h and k features observed at high-resolution (~ 0.2Å) with the long-wavelength camera of *IUE* (cf. Figure 1). The strong Mg II k (λ2795) emission core of ξ Boo A is symmetric, while that of β And is asymmetric. The deep central reversal of the emission core in β And is caused in part by absorption by interstellar Mg II, but the strong asymmetry, with the blue-shifted emission peak weaker than the red-shifted peak is likely caused by an outwardly-expanding wind at these temperatures. The mass-loss rate in β And is modest, so little circumstellar absorption is apparent. The disappearance of observable hot transition-region material occurs with the appearance of circumstellar shell absorption lines and chromospheric Mg II and Ca II line asymmetries indicating mass loss in the upper-right of the H-R diagram (Reimers 1977; Stencel 1978; Stencel and Mullan 1980).

The possible explanation for this seemingly unbroachable dichotomy of the ultraviolet character of cool outer atmospheres must be examined in light of a new category of ultraviolet spectra: the "hybrid" stars. Also shown in Figure 1, the star α Aqr (G2 Ib) possesses the hot transition-region lines such as Si IV, C IV and N V. The Mg II k line, however, is strongly asymmetric, with the blue peak depressed relative to the red, similar to that of β And and indicative of outflows in the extended atmosphere. In addition there is a strong circumstellar shell, at the relatively cool temperature of Mg II, but blue-shifted by about -70 km s^{-1}, *prima facie* evidence of a strong stellar wind.

The hybrid stars, such as α Aqr (G2 Ib), β Aqr (GO Ib), α TrA (K1 II), θ Her (K3 II), γ Aql (K3 II) and ι Aur (K3 II) (Hartmann *et al.* 1981, 1984*b*; Reimers 1982) provide a link between the hot, rarefied winds similar to that in the Sun, and the cool, dense winds in the cool supergiants. The hybrid stars populate an intermediate domain of modest winds yet these stars maintain a hot transition region with 10-100% solar transition zone surface fluxes.

One proposed explanation of the difference between the solar and nonsolar ultraviolet spectra across the H-R diagram is that wind expansion prevents the atmosphere in cool giants and supergiants from reaching the hot ($T \sim 10^5$K) transition-region temperatures because the wind provides enough cooling via adiabatic expansion (Linsky and Haisch 1979). With the discovery of the hybrid stars, however, an alternative suggestion has developed. Hartmann and MacGregor (1980) propose that stellar winds are driven by Alfven wave dissipation. In luminous stars, the extended density distribution in these atmospheres provides the extra cooling by radiation in order that the terminal velocities of the wind be small, in agreement with observations. The transition-region lines, observed to be quite broad, denote the onset of a warm wind (Hartmann *et al.* 1982*a*). Alternatively, Linsky (1982) proposed that the atmospheres of a hybrid star have two components--one with closed magnetically-confined loops responsible for most of the emission measure at high temperatures of C IV, Si IV and N V, and magnetically open structures analogous to coronal holes where most of the cool gas at Mg II temperatures escapes. The Alfven-wave-driven wind

theory, however, may well be compatible with the observational evidence provided by the hybrid stars and, therefore, may represent the same mechanism by which mass is lost on the Sun. Although the wind process is similar, the low-gravity of the evolved stars drastically alters the outer atmosphere structure. The evidence provided by the hybrid stars and its interpretation in the context of the wave-driven winds is as follows (Hartmann *et al.* 1984*b*).

Variations are evident in the short-wavelength portion of the Mg II emission in α TrA. The changes occur on timescales of a year in the high-velocity wind absorption. Neither the overall flux of the chromospheric Mg II emission nor of the high-temperature fluxes, such as C IV, varies significantly. Thus, variations are caused by the wind, far above the stellar photosphere. Not only the amount of material in the wind but also its velocity is variable. An exposure saturating the chromospheric emission cores reveals faint Mg II absorption in the wind blueshifted by -180 km s^{-1}, close to the escape velocity of the star. A terminal velocity as large as this eases the severe constraints upon wind theory that were previously imposed by observationally-biased low velocities. Such a large outflow velocity may be common among the hybrid stars; however, its discovery may be selected against by the lack of background radiation at these wavelength in these late-stellar photospheres.

The widths of the transition region lines are supersonic, evident from α TrA even in the optically thin transition region lines C III] λ1909 and Si III] λ1892, whose full widths at half-intensity are about 100 km s^{-1} and in the C IV lines about 150-200 km s^{-1}. The deposition of Alfven-driven waves in the transition region could produce mass loss rates of 10^{-9} to 10^{-10} $m_{\odot}$ yr^{-1}, consistent with observed limits (cf. Drake and Linsky 1984). The wave motions may turbulently broaden the transition zone lines to the observed widths. No evidence exists for Doppler shifts larger than 10 km s^{-1} in the high-temperature lines of α TrA. This would be consistent with the large amount of line broadening deposited at the base of the wind. Hartmann *et al.* (1982*b*) show that optically thin line profiles would be broadened nearly symmetrically by such a wave-deposition process. In α TrA, for example, the line widths produced by models of wave deposition can be 140-170 km s^{-1} in C III] and C IV, in reasonable agreement with the observed line widths (Hartmann *et al.* 1984b). Interestingly, the theoretical C IV profile, with only a marginal optical thickness ($\tau \sim 3$), is mildly P-Cygni in character with an apparent "redshift" of about + 8 km s^{-1}.

The overall picture outlined by Hartmann *et al.* (1984b) for the hybrid stars produces a cool, modest wind by a solar-type wind mechanism in stars with an extended density distribution. The turbulence in the high-temperature lines might be provided by the damping of the Alfven waves. These high-temperature lines are formed relatively close to the stellar surface, the acceleration of the wind is much further out in the atmosphere. The waves heat, and the energy is radiated in the extended density distribution of the outer atmosphere. Far out in the wind, recombination of Mg^{++} and Ca^{++} ions cause the blueshifted absorption features. The absorption features are highly variable, suggesting that the far wind is, also. The fluxes of the high-temperature lines do not measurably vary, an indication that although formed in a turbulent re-

gion, the line-forming region is close to the stellar surface. There is no direct evidence that the temperature of the wind is only a few x 10^4K and no hotter. Although no outflow velocities are apparent in the regime of C IV-N V, *IUE* provides no further information with which to probe the proposed interface between the turbulent gas at 2 x 10^5K and the cool, modest wind at 10^4K.

E. Dynamics in Ultraviolet Spectra of Cool Stars

Dynamics apparent from high-resolution spectra show small significant redshifts (less than or about 10 km s^{-1}) of the transition-region lines in slightly higher-gravity stars. In these stars the redshifts are also accompanied by supersonically broad emission lines as observed for the hybrid supergiants. Indeed, in the few high-resolution spectra of evolved stars showing transition-region lines such as β Dra (G2 Ib-II), Brown *et al.* 1984), λ And (G8 IV-III), α Aur (F9 III + G2 III), β Ceti (G9 III) (Ayres *et al.* 1983), the C IV λ1550 and Si IV (λ1400) emissions are broad, for example C IV has a width of up to 120 km s^{-1} in α Aur and 200 km s^{-1} in β Dra. Ayres *et al.* (1983) conclude that the width of these features is *not* caused by opacity effects in the line-forming region; they also suggest that the redshifted velocities are the result of small downflows in magnetically-confined, "loop" regions, as seen on the Sun. Alternatively, the origin of the redshifts may be the result of distortions caused by the deposition of Alfven waves, similar to the suspected line-broadening process in the hybrid supergiants.

III. ATMOSPHERIC INHOMOGENEITIES

Magnetic phenomena observed on the Sun can be sought on other stars. While the surfaces of most stars remain spatially unresolved, the existence of inhomogeneities can be revealed by time-serial observations. Two examples are active areas, associated with starspots, and flares.

A. Active Areas and Starspots

Detailed investigations in the visible and ultraviolet revealed surface inhomogeneities in the active-chromosphere star λ And (Baliunas and Dupree 1979, 1980, 1982). The G8 IV-III component in this 20-day (orbital period) RS CVn-type binary system has strong chromospheric emission and an unseen secondary star. For over 50 years, variations have been noted in the V-passband of up to 30% with a period of about 54 days. These modulations are likely caused by spots, dark in photospheric light, which pass through our line of sight during a stellar rotation period of 54 days. Spectra from *IUE* reveal an anticorrelation of visible light with the strength of the ultraviolet raidation (Figure 5*a*). The appearance of the spotted areas which may cover as much as 30% of the visible hemisphere corresponds to the darkening of the photometric light, and the brightening of the chromospheric and transition-region emissions. The Ca II K emission brightens in concert with the ultraviolet lines. (The flux in Mg II h and k does not measurably vary in the Baliunas and Dupree (1982) studies primarily because the phase coverage of Mg II was not complete.) The

enhancement of the chromospheric and transition region emissions at photometric light minimum are akin to those observed for sunspots and associated solar active regions.

Another RS CVn-type binary, II Peg, with an orbital period of 6.7 d, nearly synchronous with the active KO IV star's rotation period, and χ^1 Ori, a GO V star with a rotation period of 5.1 days were also monitored in the ultraviolet. In II Peg, fluxes of the chromospheric lines including Mg II and the transition region lines increased dramatically as the visual magnitude (monitored with the FES) decreased (Marstad *et al.* 1982). The enhancement of C IV, a factor of five, was the largest among the transition-region lines. The enhancement in the Mg II and other chromospheric lines was less than a factor of two. In absolute terms, however, the radiative losses over the active area in the chromospheric emission are comparable if not slightly larger than those in the transition zone. For II Peg, the shapes of the visible light curve and the ultraviolet flux curves suggest that the photospheric spots cover nearly 30% of the hemisphere while the transition-region inhomogeneity, the active area, is limited to some 6% of the hemisphere (Linsky 1984).

In the study of the behavior of the ultraviolet emission in χ^1 Ori over its rotation modulation phase, Boesgaard and Simon (1984) find a contrast in the transition zone fluxes of factor of about two in C IV. The He II (λ1640) feature and chromospheric Ca II K flux also correlates with the behavior of C IV. Interestingly, significant variations detected in the emission flux of N V, O I (λ1305), C II (λ1335), Si IV and C I (λ1657) do not always correlate with those of C IV. The Mg II emission does not measurably vary, but in terms of absolute losses, the lack of any variation is not troublesome. On χ^1 Ori, then, the picture emerges that low-chromosphere species have contrasts of 3-5 times the quiet regions and can be coincident with the higher-level lines. These regions producing the lower-lying emissions may not be long lived. The most persistent inhomogeneities appear in C IV, possibly in phase over 325 days, and covering some 40% of the hemisphere at maximum emission.

B. Stellar Flares

Ultraviolet spectra from *IUE* of stellar flares provide important constraints for theories of flare mechanisms. Flares in dMe stars are well-documented in visible light, and additional information results from ultraviolet measurements of flares in Proxima Centauri (dM5e, Haisch *et al.* 1983), Gl 867A (dM2e, Butler *et al.* 1981), and EQ Peg B (dM5.5e, Baliunas and Raymond 1984). In addition, flares in the ultraviolet have been detected from active chromosphere stars whose photospheres are hotter than those of the dMe stars and overwhelm the visible light variations present in the flares, for example, in UX Ari (KO IV, Simon *et al.* 1980) and λ And (G8 IV-III) (Baliunas *et al.* 1984). With supplemental X-ray measurements, Haisch (1983) concludes that the stellar flares, observed primarily among the dMe stars, are similar to moderate solar flares in terms of temperatures, inferred loop lengths, emission measures and luminosities, but with shorter decay times compatible with densities about an order of magnitude higher than in solar flares.

The flare observed from λ And (Figure 6) was remarkable in that the enhancement of factors of several in the transition-region lines persisted for over six hours. The energy radiated just in the ultraviolet was in excess of about 10^{35} ergs. The energy present in the ultraviolet is a few orders of magnitude greater than that of the largest solar flares. For this flare, both the Mg II and H I ly α emissions were measured. In Mg II h and k, the energy radiated is five times that of C IV, although the contrast of the increase in C IV is larger than for Mg II. The enormous radiative losses in Mg II and H I Ly α are obscured by the small percent changes in these strong lines. The nonradiative input of energy during the flare is at least comparable in the chromosphere and transition region. The input of this energy in the flaring component of the atmopshere of λ And must be sustained over the duration of the event.

In the dMe stars Gl 867A (Butler *et al.* 1981) and EQ Peg B (Baliunas and Raymond 1984), the ultraviolet flare is also accompanied by the appearance of detectable continuum emission in the wavelength region λλ1700-2000 (Figure 7). The ultraviolet continuum is consistent with models that produce such emission (along with Balmer line emission) in the chromosphere at temperatures near 10^4K (Katsova, Kosovichev and Livshitz 1981).

The ultraviolet fluxes during the flare in EQ Peg B are similar to those either in the thermal phases of large, two-ribbon solar flare where radiative cooling balances thermal conduction or in gas cooling quickly from X-ray emitting temperatures (Baliunas and Raymond 1984).

The ultraviolet observations available from *IUE* are providing information on outer atmospheres of cool stars at a challenging pace. Studies of time variations have revealed atmospheric inhomogeneities, such as the counterparts to active regions and flares. The parameters controlling chromospheric and coronal emission are being sorted out by surveys of ultraviolet emission. Additionally, mechanisms thought to balance the energy budget in the solar atmosphere are being extended and tested across the H-R diagram.

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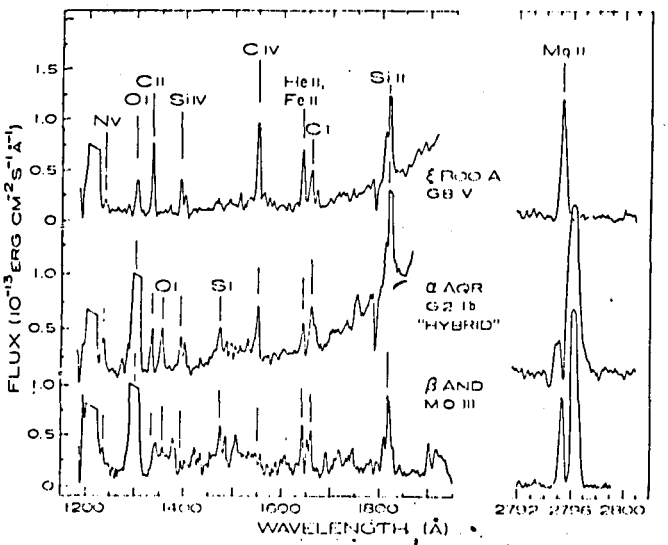


Figure 1 -- *IUE* ultraviolet, short-wavelength spectra (left) and high-resolution Mg II (right) spectra of an active chromosphere dwarf, ξ Boo A, a "hybrid"-atmosphere star α Aqr, and a giant, β And. In the short-wavelength spectra, the presence of high-temperature gas is indicated by N V, C IV and Si IV in ξ Boo A and α Aqr. The star β And shows no observable amounts of these transition-region lines. In α Aqr and β And, the Mg II-k profile suggests mass outflow by the asymmetry of the emission peaks (violet peak weaker than red), and in addition, blue-shifted absorption is present at about -70 km s^{-1} in α Aqr (Dupree 1983, by permission of the author).

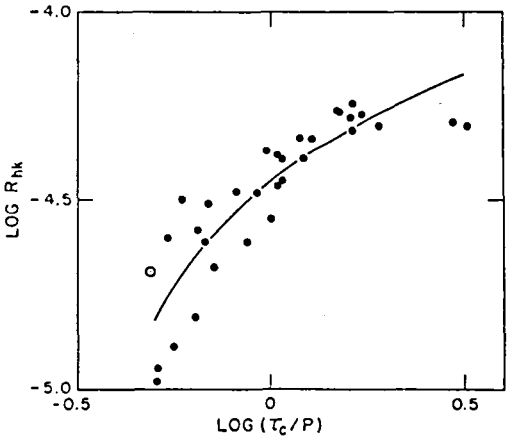


Figure 2 -- Mg II h and k emission, normalized by the stellar bolometric luminosity as a function of τ/P in lower main sequence stars. The rotation period is P, and τ is a function of (B-V), or main sequence mass, alone. The parameter τ is similar to the convective turnover time for α = 2. The Sun is denoted by its symbol "⊙". The solid line is the fit of Ca II emission as a function of τ/P, with a vertical displacement to account for the larger fluxes in Mg II compared to Ca II (Hartmann *et al.* 1984*a*, by permission of the authors).

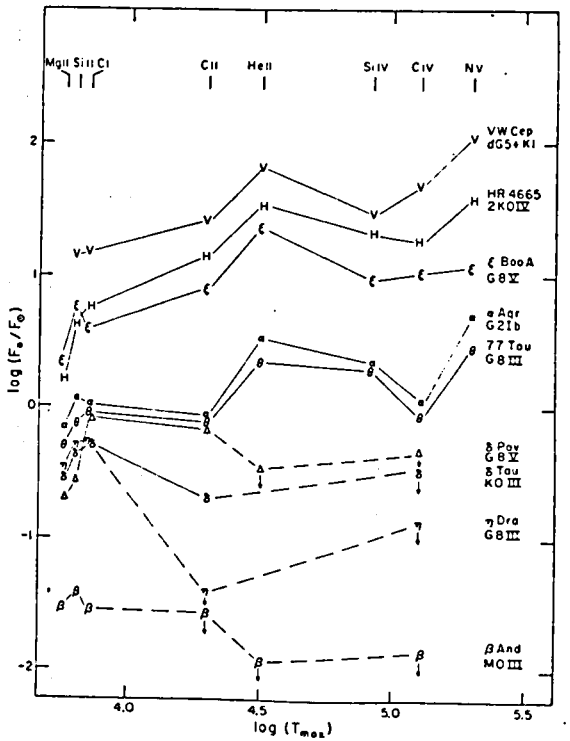


Figure 3 -- Stellar surface fluxes relative to quiet Sun surface fluxes as a function of approximate temperature of formation of ions in a variety of cool stars. Note the paucity of high-temperature material relative to the Sun in, for example, δ Tau. In more active stars, such as VW Cep, the transition-region emission increases faster than the chromospheric fluxes (Hartmann *et al.* 1982*a*, by permission of the authors).

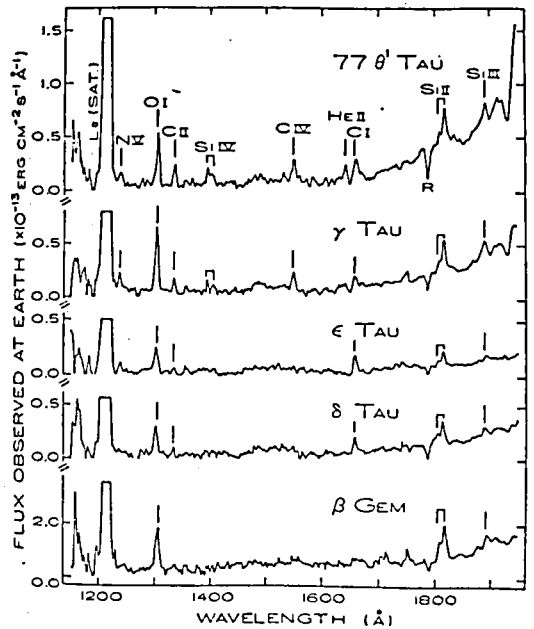
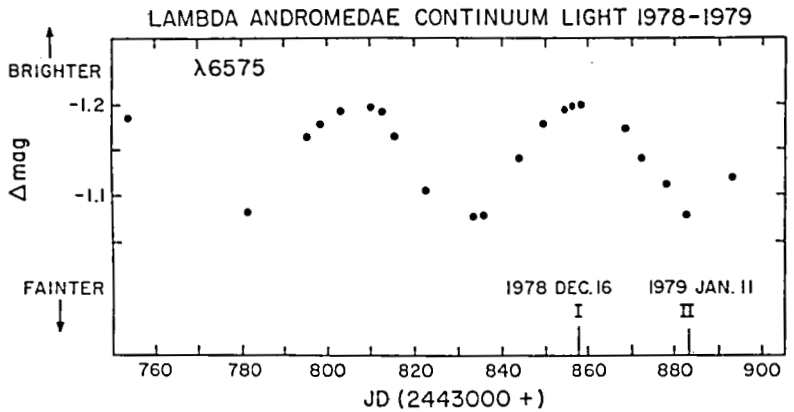


Figure 4 -- *IUE*, short-wavelength, low resolution spectra of the four Hyades giants (KO III) compared to the field star β Gem. Note the presence of high-temperature, transition-region lines (N V, C IV, Si IV) in 77 Tau and γ Tau, which are not detected in ε Tau, δ Tau and the field star β Gem. The presence of high-temperature material in 77 Tau and γ Tau is correlated with increased emission in Ca II and Mg II compared to the other stars (Baliunas 1983*a*, by permission of the authors).



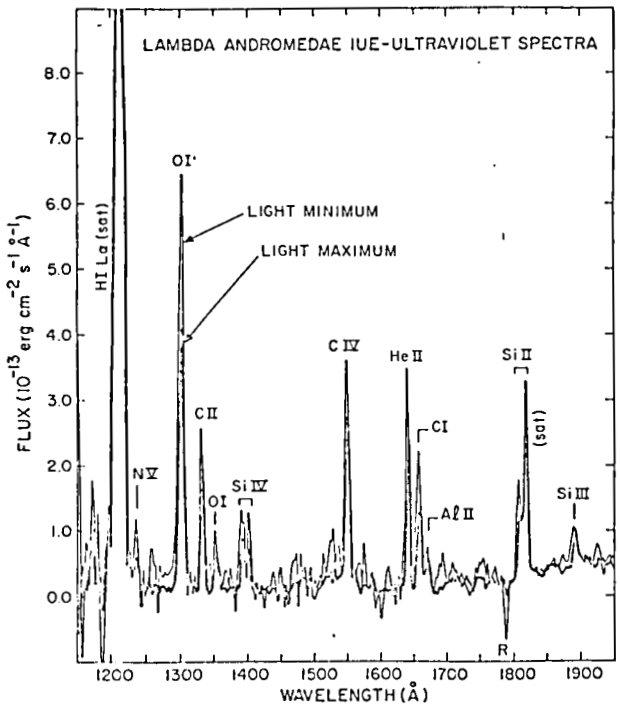


Figure 5 -- (a) The photometric modulation of λ And (G8 III-IV + ?) caused by visibly dark starspot areas during stellar rotation with a period of about 54 days. For the times of maximum and minimum light, marked on the plot, the *IUE*, short-wavelength spectra (*b*) show an anti-correlation of ultraviolet emission with light, similar to the behavior of active regions overlying sunspots on the Sun (Baliunas and Dupree 1982, by permission of the authors).

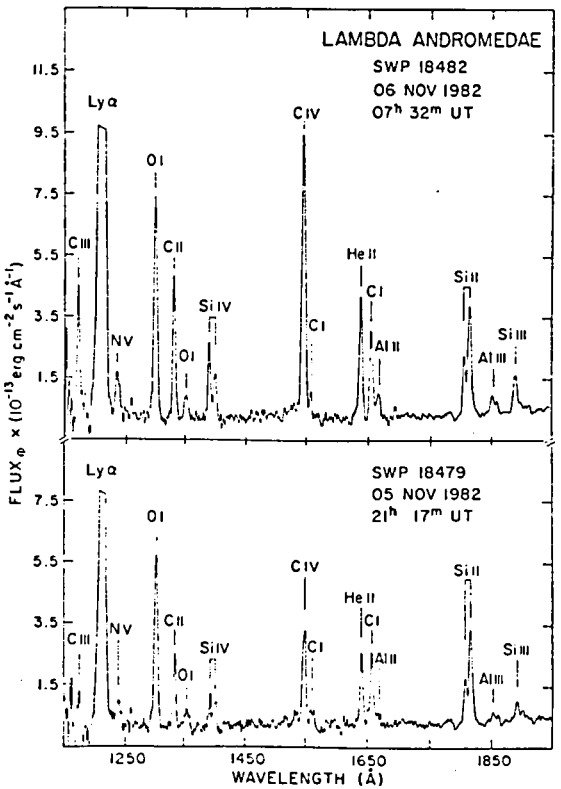


Figure 6 -- *IUE*, short-wavelength spectra during (above) and before (below) a flare lasting over six hours on λ And. The largest enhancement is observed in C IV (Baliunas *et al.* 1984), by permission of the authors).

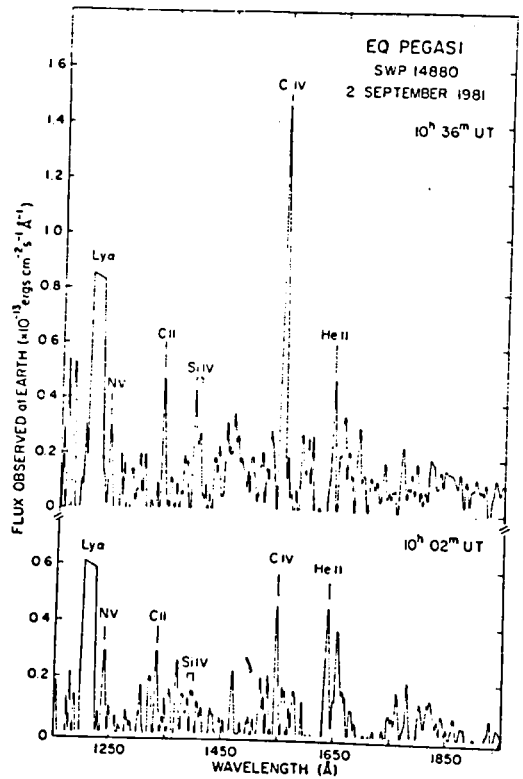


Figure 7 -- *IUE*, short wavelength spectra during (above) and before (below) a flare on EQ Peg (dM4.5e + dM5.5e). Note the appearance of continuous emission (λλ1750-1950) during the flare (Baliunas and Raymond 1984, by permission of the authors).